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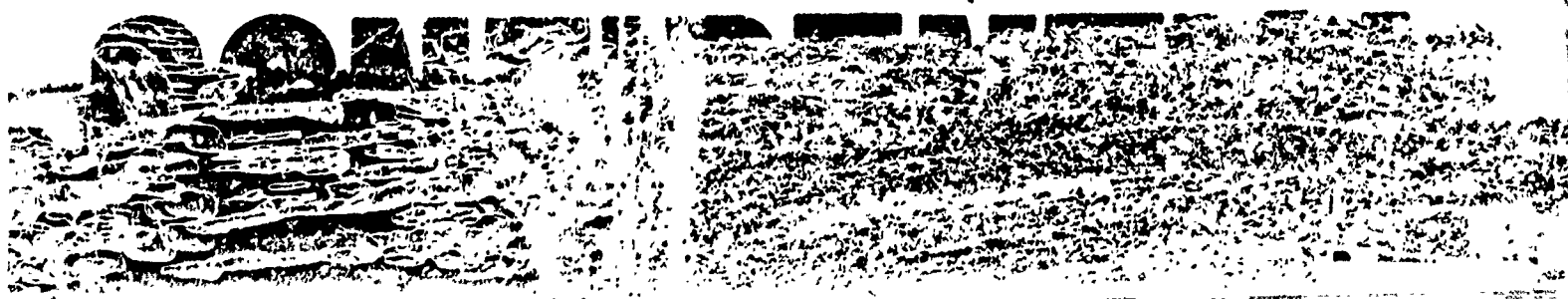
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MEMORANDUM REPORT NO. 1231

SEPTEMBER 1959

SHAPED CHARGE PERFORMANCE WITH LINEAR FLUTED LINERS (U)

J. SIMON

R. DIPERSIO

R. J. EICHELBERGER

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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MEMORANDUM REPORT NO. 1231

JSimon/RDiPersio/
RJEichelberger/djp
Aberdeen Proving Ground, Md.
September 1959

SHAPED CHARGE PERFORMANCE WITH LINEAR FLUTED LINERS (U)

(CONFIDENTIAL)   ABSTRACT

Experimental results are described which show that orthodox spin-compensating liners, with flute depth a linear function of liner radius, produce compensation at different rotational frequencies for various elements of the liner. As a result of this dispersion in optimum frequency, the maximum penetration obtained at the mean optimum frequency of the liner is less than the potential penetration that could be realized from a given charge design. The higher the spin rate for which such a liner is designed, the greater the dispersion and the lower the attainable penetration.

The experimental observations are analyzed to show the means by which dispersion can be reduced or eliminated, and penetration at high spin frequencies materially improved. Explanation of earlier failures in attempts to apply spin compensation to HEAT rounds is also derived from the results.

(CONFIDENTIAL)   I.   INTRODUCTION

It has been known for many years that the penetration produced by a
rotated, metal-lined shaped charge is greatly reduced from its non-rotated
performance [1]*. The reason is clear from the flash radiographs of jets
produced by non-rotated and rotated shaped charge liners, shown in Figure
1. The non-rotated charge produces a jet that remains coherent and concen-
trated along the charge axis. The jet from the rotated charge has a radial
spread of particles, which results in a decrease in the depth of penetration
in the target material. The cause of the spread of the jet lies in the
requirement that the angular momentum of the metal liner must be conserved
during the processes of liner collapse and jet formation. This results in
centrifugal forces that spread the jet, thus causing the energy of the jet
to be dissipated over a larger area of the target surface [2]. A typical
curve of penetration as a function of rotational frequency is shown in
Figure 2.

Several methods have been devised to modify the shaped charge liner to
reduce or eliminate the deleterious effect of spin on penetration. This
report will be concerned with the most tested method - the use of straight
flutes impressed in the outer and inner surfaces of the liner [3]. Photographs
of a smooth and a fluted liner are shown in Figure 3. A cross-section of a
fluted liner with the various design parameters listed and defined is shown
in Figure 4.

The principle behind spin compensation is to divert a very small portion
of the energy of the detonating high explosive to impart, to the material
forming the jet, a tangential component of velocity which will counteract
that introduced by the initial rotation. If the added tangential velocity
component of each section of the liner is equal and opposite to its tangential
velocity due to rotation, the liner will collapse and form a jet as if the
liner were smooth and had no initial rotation.

---

*   Refers to references listed at end of report.

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The tangential velocity imparted to an element of a conical liner due to its rotation is proportional to its distance from the liner axis, $V_t = 2\pi r \nu$ where:

V_t = tangential velocity due to liner rotation

r = radial distance from liner axis to element of liner

ν = frequency of rotation of liner

In almost all of the tests on fluted liners to date, the flute depth has been varied linearly from a nominal zero value at the geometric cone apex to a maximum at the cone base.

Previous investigators [4] have stated that the simple "linear" flute (i.e., a flute whose depth is a linear function of liner radius) was not the ideal design, and that a non-linear flute design was necessary. In the initial experiments, however, no method was available for determining the ideal design, so that the simplest flute, from the point of view of production, was adopted. This results in a design such that the various ring elements of a liner do not have the same optimum frequency and do not all give their maximum potential penetration at any given frequency. The integrated result for the entire cone is that the maximum penetration (at the mean optimum frequency of all the ring elements) is considerably less than the potential penetration. The higher the spin frequency at which a liner is designed to operate, the greater the dispersion in optimum frequencies for the various elements, and the lower the total penetration. Theoretically, an ideal flute should eliminate dispersion in optimum frequency and a fluted liner should provide penetration equal to that of a similar smooth liner fired without rotation.

The purpose of the current research program in spin compensation is to investigate the validity of the basic hypothesis that all elements of a given linear fluted liner are not compensated at the same spin rate and to determine what modifications in flute design are required to reduce or eliminate dispersion at high rotational frequencies.

The experimental results reported herein consist of observations obtained by flash radiographic techniques [5] [6], radioactive tracer methods [7] [8] [9], and penetration-rotation firings [10].

(CONFIDENTIAL)   II.   LINER DESIGN

The series of fluted liners investigated were manufactured by the Thomas Industries, Inc., Fort Atkinson, Wisconsin under Contract No. DA-11-022-ORD-2147. The liners were part of a group of five scaled sizes that varied in diameter from a nominal one inch to five inches. The sizes specifically experimented with are those designated BRL-3, and BRL-4. Pertinent drawings and specifications for liner design are Thomas Industries Drawing No. 464008, and Carnegie Institute of Technology Drawing Numbers 1455 thru 1460, and 1389a. The charge design is illustrated in Figure 5.

The design parameters for a linear fluted cone are shown in Figure 4. The group of liners ($42°$ apex angle) described herein will be represented by the nomenclature of a BRL-1 (as an example): 0.945 $\{(0.035)(16x.0100)\ (S,S)(\delta)\}$. BRL-1, 0.945 describes the No. 1 scale liner with a cone diameter of 0.945 inches; the number 0.035 represents the average wall thickness (perpendicular to the wall) in inches; the figures (16x.0100) represent the number of flutes and flute depth at a datum plane near the base of the liner (these liners have 16 flutes and have an exterior flute transverse depth of 0.0100 inches at the base datum plane); the nomenclature (S,S) refers to the method of manufacture (the liners were fluted between matching metal fluted tools); the symbol δ refers to the relative angular indexing of punch and die. For each series, ten index angles and the smooth parent liner were tested. Since these liners are from a scaled series, the representative nomenclature for BRL-3 and BRL-4 sizes are:

$$BRL-3,\ 2.835\ \left\{0.105\ (16x.0300)\ (S,S)\ (\delta)\right\}$$
$$BRL-4,\ 3.780\ \left\{0.140\ (16x.0400)\ (S,S)\ (\delta)\right\}$$

The liners were assembled into scaled casings; the confining wall thickness and all other dimensions, and weight of composition B high explosive filler, were scaled.

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(CONFIDENTIAL)   III. EXPERIMENTAL RESULTS

With the (S,S) type linear flute, the direction of optimum compensation frequency for best performance varies with the index angle [11], the convention adopted for the sign of rotation direction is the following: A rotation is considered positive if the exterior offset surface leads the canted surface; it is negative if the offset surface trails the canted surface. The arrow above the flute profile in Figure 4 indicates a positive rotation. With this convention in sign, a reversal of the flute orientation does not change the sign of the optimum frequency, although the actual direction of rotation in a fixed coordinate system is thereby reversed.

A. Penetration-Rotation Firings.

The penetration-rotation firings were conducted at Erie Ordnance Depot under the supervision of Firestone Tire and Rubber Co. [10] (Contract No. DA-33-019-ORD-2355). The optimum frequency versus index angle for the BRL-3 and BRL-4 liners are shown in Figure 6, along with the normalized penetrations versus index angle for the two sizes. The penetration by the parent smooth liners, unrotated, is represented by the dashed line. The maximum penetration and optimum compensation frequency for each index angle are shown in Table I.

TABLE I

Optimum Spin-Rate and Maximum Penetration
at Various Index Angles for BRL No. 3 and BRL No. 4 Charges [10]

Index Angle (degrees)	BRL No. 3C			BRL No. 4C		
	Spin Rate (RPS)	Penetration into mild steel (inches)	Maximum Penetration in Cone Diameters at Optimum Spin-Rate	Spin Rate (RPS)	Penetration into Mild Steel (inches)	Maximum Pentration in Cone Diameters at Optimum Spin-Rate
0	+60	13.6	4.80	+50	18.0	4.75
1	+50	13.7	4.85	+30	20.6	5.44
2	+15	15.2	5.38	0	20.5	5.40
4	-35	14.6	5.15	-35	19.6	5.17
6	-50	14.0	4.95	-45	19.0	5.01
8	-50	14.0	4.95	-35	18.0	4.75
10	-25	13.6	4.80	-20	17.8	4.68
14	+15	12.5	4.41	+15	15.8	4.18
18	+60	12.4	4.38	+40	16.0	4.22
21.5	+80	13.8	4.88	+65	18.5	4.88
Control Smooth Liner	Non-rotated	16.6	5.88	Non-rotated	22.3	5.88

One observes in Figure 6 that the optimum frequency falls from a maximum positive value at an index angle of ?1.5°, crosses the zero frequency axis at an index angle between 2° and 3°, changes sign and proceeds to a maximum negative value at about 7°; it returns to zero, reverses sign again and increases to its positive maximum.

The penetrations into mild steel by smooth BRL-3 and BRL-4 liners are 16.6 inches and 22.3 inches, respectively. The top curve in Figure 6 shows that the efficiency of compensation (i.e., the percentage of penetration of the smooth parent liner) is greatest (92% for both sizes) with index angle 2°. However, at this index angle, the optimum compensation frequency is low (approximately zero rpc). The degree of compensation at the maximum negative value of compensation frequency ($\theta \div 7°$) is 85%, and at the maximum positive value of frequency ($\theta = 21.5°$) is 83%. It should be noted that there is no simple relationship between optimum frequency and efficiency of compensation. For example, a magnitude of 30 rpc can be obtained with the 4C liners at index angles of (approximately) 1°, 3°, 9.5°, and 16 degrees. The corresponding compensation efficiencies are, respectively, 82%, 91%, 80%, and 73%. Differences become much greater when liners are designed for higher frequencies.

B   Flash Radiography.

The experimental plan required the use of samples from each group of liners for flash radiographic observation. Triple flash radiographs of jets from each type of liner were obtained at each of several rotational frequencies at time intervals of 115, 165, and 1?? microseconds after detonation. Elements along the jet were examined for indications of compensation, and the compensation frequencies of the front, center, and rear portions of the jet were estimated. Jet elements that were continuous or only slightly fragmented were considered to be compensated at the test frequency, whereas jet elements that were badly fragmented or bifurcated were considered uncompensated. The photograph of the jet in free flight could be observed over the range of several inches to 52", which is the full length of the x-ray film cassette.

Flash radiographs illustrating the variation in optimum frequency along the jet are shown in Figure 7. For an index angle of zero degrees the rear of the jet is compensated at 120 rps (Figure 7a), the front of the jet at 30 rps (Figure 7b). For the 6° index angle, the optimum frequency for the front of the jet is -100 rps (Figure 7c), and -20 rps for the rear of the jet (Figure 7d).

The data showing the compensation frequency of elements of the BRL-3 and BRL-4 liners, as deduced from flash radiographs, are found in Table II; the spin rate versus relative position of jet element is plotted in Figure 8. For index angles that produce compensation in the positive region of frequency, the front of the jet compensates at a lower frequency that the rear. For index angles that compensate in the negative region, the front portion of the jet compensates at a higher (absolute value of) frequency than the rear.

The optimum rotational frequency versus index angle, and the penetration versus index angle, are plotted in Figure 9 for the linear fluted liner (BRL-3). Curves a, b, and c represent the rear of the jet, the middle of the jet, and the tip of jet, respectively. Comparison with Figure 6 shows that the "mean" curve obtained from penetration observations lies between those representing the middle of the jet and the rear, as would be expected for short standoff penetrations. The penetration curve (d in Figure 9) illustrates that the maximum penetration occurs when the dispersion in optimum frequency between front and rear of the jet is at a minimum (index angle region of 2°).

C. Radioactive Tracer Techniques.

The application of radioactive tracer isotopes to the study of shaped charge phenomena was initially investigated at Carnegie Institute of Technology [7]. Recently Mr. M. K. Gainer [9] of the BRL, in cooperation with Dr. V. Lamb and Mr. H. I. Salmon of the National Bureau of Standards [8], has refined the techniques to warrant its use as a research tool with fluted liners.

Silver (Ag 110) is electrodeposited in bands at predetermined positions on the inside of the liner. The locations of the bands were 1/2", 1", 1 1/2", 2", 2 1/2" and 3" from the bottom of the liner flange to the near edge of the band; the locations are designated A, B, C, D, E, and F, respectively.

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TABLE II

Compensation Frequencies
Determined from Flash Radiographs of Jets

LINER		COMPENSATION FREQUENCY (RPS)		
TYPE	Index Angle	Front of Jet	Middle Portion of Jet	Rear of Jet
3C	$0°$	60	80	120
	$1°$	30	45	75
	$2°$	10	20	45
	$4°$	-80	-60	-20
	$6°$	-90	-60	-20
	$10°$	-70	-45	20
	$21\text{-}1/2°$	70	100	120

Flute Depth = .030", Wall Thickness = 0.105"

4C	$0°$	30	50	75
	$1°$	15	20	60
	$6°$	-90	-45	-15
	$21\text{-}1/2°$	45	75	90

Flute Depth = .040", Wall Thickness = 0.140"

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The approximate thickness of radioactive deposit varied from 0.00004" to 0.0012". The activity of Ag 110 varied from 300 to 170 micro curies. The band width was nominally 1/16" + 0.003". A group of liners were plated with single radioactive bands, while other liners were plated with six bands.

Radioactively tagged liners of the BM-4 linear-fluted type (index angle 6°) were fired into mild steel target plates (12" x 12" x 1") and the depth reached by the tagged zonal element was determined by radioactive assay of the plates. The relation between penetration depth and position of a zonal element in the liner was obtained in this manner.

The results of firings of the tracer-tagged liners are given in Table III, and are plotted in Figure 10. The greatest contribution to penetration (for the charge design used) is produced by the liner zone 1/2" to 1" from the base of the cone (total inside cone height 4 1/2"). The penetration effectiveness of each zone changes, however, as the frequency is varied. At the low frequencies of rotation (0 to -20 rps), the greatest penetration is produced by the first 1/2" zone from the base. As the frequency is increased (in the negative direction), the zone from 1/2" to 1" of the base becomes predominant. This condition remains throughout most of the useful frequency range of this charge, which has its <u>mean</u> optimum frequency in the region of -45 rps to -55 rps at a 12" standoff. At a frequency of -75 rps, the zone 1" to 1 1/2" from the base produces the greatest part of the penetration, but the total penetration is considerably decreased.

These results substantiate the radiographic observations (for index angles that give a negative optimum compensation frequency), which show that the indications of compensation shift from the rear to the tip of the jet as the frequency increases from zero in the negative direction (Figure 7c and 7d). This would account for the shift in penetration effectiveness from the base toward the apex as the frequency changes in this manner.

The dominant role of the lower portion of the liner in penetration by heavily confined charges has been predicted on theoretical grounds, but the degree to which it predominates, as evident from the tracer results, is

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nonetheless surprising. The sum of the maximum penetrations for the various zones at their respective optimum frequencies is greater than the total penetration by the smooth parent liner fired non-rotated. The values of penetration for the zones 1/2" to 1" at -45 rps, and 1" to 1 1/2" at -75 rps are undoubtedly high, presumably due to experimental error. With refinements in experimental techniques, it is expected these values will be lowered.

TABLE III

Location (distance from top of target) of elements of radioactive tagged liners in target. BRT-4 linear-fluted liners (6° index angle), rotated; standoff, 12"; target, stacked 12" x 12" x 1" mild steel plates.

Cone Element	SPIN-RATE (RPS)								
	0	-20	-35	-45	-55	-75	-90	-100	-105
D, E, F		All	bands	located	in first	target	plate		
C	2"	2"	2"	2"	-	2"	2"	1"	1"
B	4"	4"	4"	4"	5"	12"	-	-	-
A	5"	10"	17"	19"	20"	17"	-	-	-
Total Penetration	7-1/2"	12"	18"	19-1/4"	20/1/2"	17-1/2"	10"	6-1/2"	6-3/4"

(CONFIDENTIAL) IV. DISCUSSION

A. Modification of Flute Design.

The experimental results described in the foregoing sections clearly demonstrate the validity of the hypothesis which has constituted the focal point of recent work in spin compensation: The loss in penetration in designing liners for higher spin rates has been due to an increasing dispersion in optimum frequency of the liner elements. Surprisingly, however, the direction of variation of the magnitude of optimum frequency along the liner depends upon the direction of the impulse - i.e., upon the index angle.

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The observations serve as more than qualitative substantiation of the hypothesis; they also provide the data necessary to correct the flute design and reduce or eliminate dispersion. By correlating the radiographic and radioactive tracer data, one obtains the representation shown in Figure 11 for the relation between the tangential velocity due to rotation and that produced by the compensating impulse, for liners compensating in the positive sense (index angle 21.5°). Initial spin rate has been chosen so that the base of the liner would be compensated, but the remainder of the liner benefits only slightly from the fluting at that spin rate.

Since the compensating impulse is a linear function of flute depth [3], the modification in flute design needed to remove the dispersion can also be deduced. The result, for this particular situation, is shown in Figure 12. A liner having a non-linear flute of the design indicated should afford compensation at a spin frequency of 120 rps, with little dispersion and, consequently, little loss in penetration - if the current correlations are accurate.

Similar results obtained for a liner designed to compensate in the negative sense (index angle 6°) are shown in Figures 13 and 14. In this case, the non-linear flute indicated would provide compensation at a frequency of only -40 rps, using the same maximum flute depth as in the previous case.

The results of this analysis show a clear preference for liners having index angles that produce compensation at positive rotational frequencies, in order to obtain high frequencies without excessive flute depth. In past work, with linear flutes, index angles of the order of 6 to 7° gave best results because of the less dispersion among elements contributing most to penetration.

The anticipated performance characteristics of liners having the suggested non-linear flutes are illustrated in Figures 15 and 16. In each case, the dispersion of optimum frequency is reduced and penetration is increased, relative to a liner having linear flutes, over a range of index angles adjacent to that for which the flute is designed. At other index angles, performance is poorer than that obtained with linear flutes.

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B. Interaction Between Compensation Frequency Dispersion and Effects
of Confinement.

In 1951 the Picatinny Arsenal attempted to adapt to the M307, 57mm HEAT
round, fluted liners that had been tested and found to perform satisfactorily
by Carnegie Institute of Technology. The results obtained were extremely
disappointing and only conjectural explanations could be given at the time.

In the course of the application, the conditions under which the liners
were used were significantly changed. In the initial laboratory tests at
Carnegie Institute of Technology, the charges had been confined in relatively
light bodies, made of thin-walled aluminum; the standard M307 HEAT shell, on
the other hand, is a relatively thick-walled steel body. The results
described in this report provide a ready and an entirely plausible explanation
for the drastic difference in performance between the laboratory tests and the
firings with the shell bodies.

The effect of the change in confinement upon the collapse of the liner is
represented schematically in Figure 17. In the plot are shown two curves of
the velocity of liner collapse as a function of position on the liner - one
for lightly confined charges and one for heavily confined charges. The effect
of the increased confinement is to produce a more nearly steady-state collapse
in the upper portion of the liner and to increase the rate of change of
collapse velocity in the bottom portion. As a consequence, the jet formed by
a heavily confined charge has little gradient in the front, but a very large
gradient at the rear. The contribution to penetration by the front portion
of the jet is correspondingly reduced (especially at short standoff) and the
contribution by lower portions of the liner is considerably increased. Figure
18 shows experimental data [9] for similar charges fired with light confinement
and with very heavy confinement. The plot shows the contribution to penetration
per unit height of liner as a function of the position of the liner element.
For the lightly confined charges, the peak occurs at a point between 60 and 70%
of the distance from apex toward base of the liner and the curve is qu' broad.
For the heavily confined charges, the peak occurs at a point approximately 95%
of the distance from apex to base and the rise and fall of the curve are quite
sharp.

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If it is assumed that the tangential component of collapse velocity for a linear flute is proportional to the resultant collapse velocity as shown in Figure 17, the reason for drastically different performances of lightly confined and heavily confined charges can be readily seen. By comparing Figures 17 and 18, it is evident that the greatest contribution to penetration by the heavily conf l charge is derived from a portion of the liner in which the compensation frequency is varying most rapidly with position on the liner. As a consequence, it can be expected that the most important part of the jet from the heavily confined charge will suffer a great deal of dispersion in optimum frequency and severe degradation in its penetrating ability. On the other hand, for the lightly confined charge the rate of change of optimum frequency with position is relatively slow for the portion of the liner contributing the major part of the penetration, and the dispersion would be expected to be relatively slight. Consequently, for the situation represented in Figures 17 and 18, it would be expected that from a given liner a greater total depth of penetration would be obtained from a lightly confined charge than from a heavily confined charge. For this same situation, however, it could be anticipated that the mean optimum frequency would be somewhat greater for the heavily confined than for the lightly confined charge.

It is clear from this type of reasoning that the relative performance of lightly confined and heavily confined charges containing the same fluted liner will be sensitive to details of charge design and the consequent variations in the collapse velocity and the compensation impulse curves. It is entirely feasible to design conditions under which the heavily confined charge would produce a lower mean optimum frequency than the lightly confined charge, or a greater total depth of penetration at the mean optimum frequency, or even both.

For purposes of application of the spin-compensated liner, the important conclusion drawn from the above arguments is that a liner intended for use in a heavily confined round must be especially designed for those conditions and tested in rounds that provide approximately the same degree of confinement as the ultimate shell body. Figure 19 represents, schematically, the appropriate curves of flute depth versus position of element to provide compensation with minimum dispersion f · lightly confined and heavily confined charges, respectively, assuming conditions as represented by Figure 17.

(CONFIDENTIAL)   V.   CONCLUSIONS

The conclusions derived from the observations and analysis described in the foregoing are, briefly, as follows:

(1) The basic hypothesis of the current research program on spin compensation has been proven valid. It has been shown that fluted liners having flute depth increasing linearly with liner radius do not compensate at a single rotational frequency, at least in orthodox charges.

(2) The suggested method of overcoming the deficiency of orthodox fluted liners is to change the relationship between flute depth and liner radius. Instead of the linear relationship, a non-linear relationship is needed.

(3) The type of modification to the linear flute design is illustrated in Figure 20. For liners that intrinsically compensate in the (arbitrarily defined) positive sense of rotation, a relationship as illustrated by the upper curve would be appropriate; for liners that compensate in the negative sense of rotation, the lower curve would be appropriate.

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(UNCLASSIFIED)   VI. ACKNOWLEDGMENTS

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(UNCLASSIFIED)   VII.   REFERENCES

1. a. Tuck, James L. "A Note on the Theory of the Monroe Effect", AC3596
        PHYS/EX 393, SC3, Explosives Research Committee, Shape Charge Sub-
        Committee, February 27, 1943.

    b. Paul, M. A., McDougal, D. P. and Durcek, E. J. "Target Penetration
        by the Jet from a Rotating Cone Charge", OSRD 1680, Explosives
        Research Laboratory, Bruceton, Pennsylvania, August 1943.

    c. Trinks, Walter "Mathematical Study of Lined Hollow Charges", Report
        43/6, Translated as OTIB No. 1464, April 30, 1943.

2. Litchfield, E. L., Becker, K. R., Eichelberber, R. J. and Beitel, F. P.
    "Rotated Charg s", Sixth Bimonthly Report, Carnegie Institute of Technology,
    Contract No. DA-36-061-ORD-291, CIT-ORD-R-32, 31 October 1953, p48.

3. Eichelberger, R. J. "Spin Compensation", Chapter VII, BRL Report No. 905,
    Critical Review of Shaped Charge Information, BRL, APG, Md., May 1954.

4. a. Pugh, E. M., Eichelberger, P. J. and Litchfield, E. "Rotated Charges",
        CIT-ORD-R6, June 30, 1949.

    b. Eichelberger, R. J. "Status of Spin Compensation Development", OCSCRR,
        No. 2-57, April 1957.

5. Kronman, S., Simon, J., Payfield, F. and Zernov L. "A Triple Flash Field
    Radiography System for Studying Jets from Large Shaped Charges", BRL
    Memorandum No. 659, March 1953.

6. Zernov, L. and Simon, J. "Flash Railographic Study of Special Liners for
    Shaped Charges (U)", BRL Memorandum No. 936, June 1955.

7. Bryan, G. M., Eichelberger, R. J., MacDonald, D. and Zigman, P. E.
    "Application of Radioactive Tracers to the Study of Shaped Charge Phenomena",
    Journal of Applied Physics, Volume 28, No. 10, 1152-1155, October 1957.

8. Lamb, V. A. and Salmon, H. T. "Electrodeposition of Radioactive Tracers
    on Shaped Charge Liners". National Bureau of Standards, Washington, D. C.
                        NBS 5943 - March 31, 1958
                        NBS 5957 - June 30, 1958
                        NBS 6230 - December 31, 1958
                        NBS 6364 - March 31, 1959

9. Gainer, M. K. "The Application of Radioactive Tracers to Shaped Charge
    Liners", BRL Memorandum Report in process of publication.

10. Firestone Tire and Rubber Company, Progress Report on the Research and Development on Shaped Charge Liners, Contract No. DA-33-019-ORD 2355, Defense Research Division, Akron, Ohio.
    Fifth Quarterly Progress Report - Dec., Jan., Feb., 1957-1958
    Sixth Quarterly Progress Report - March, April, May 1958
    Seventh Quarterly Progress Report - June, July, Aug., 1958

11. a. Pugh, E. M., Eichelberger, R. J., Litchfield, E. L., and Beitel, F. P. "Rotated Charges", First Bimonthly, CIT-ORD-R-21, December 31, 1951, Contract No. DA-36-061-ORD-122.

    b. Rostoker, N. and Eichelberger, R. J. "Rotated Charges", Fourth Bimonthly, CIT-ORD-R-24, June 30, 1952, Contract No. DA-36-061-ORD-122.

    c. Beitel, F. P., Eichelberger, R. J., Litchfield, E. L. and Pugh, E. M. "Rotated Charges", Third Bimonthly, CIT-ORD-R-23, 30 April 1951, Contract No. DA-36-061-ORD-122.
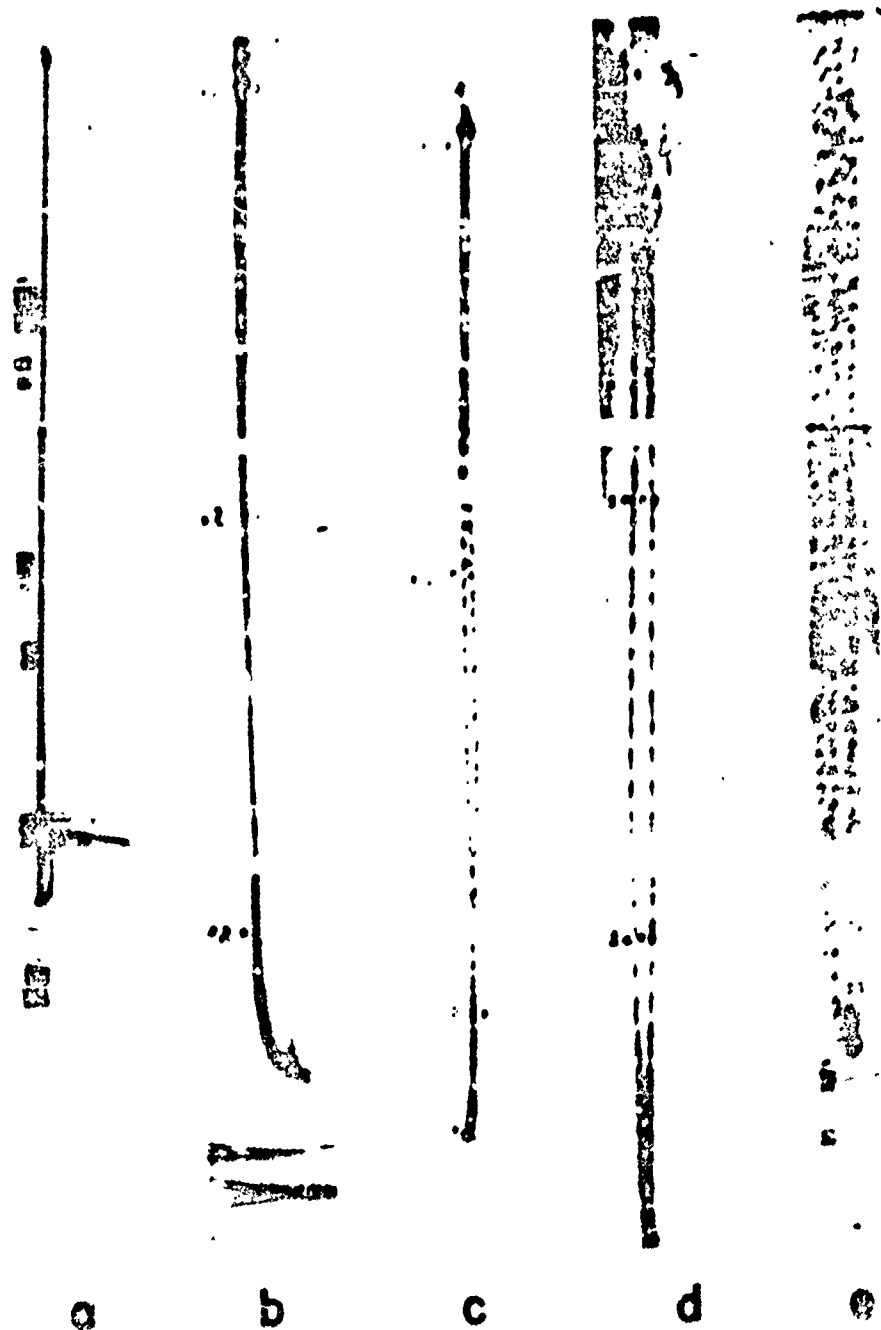
FIGURE I

THE JET OF A SMOOTH I05 MM LINER IS SHOWN
TO SPREAD WHEN THE SHAPED CHARGE IS ROTATED.
ROTATIONAL FREQUFNCIES FOR THESE JETS ARE a)
0 RPS, b) I5 RPS, c) 30 RPS, d) 45 RPS, AND e)60.

STANDOFF: 7 1/2"
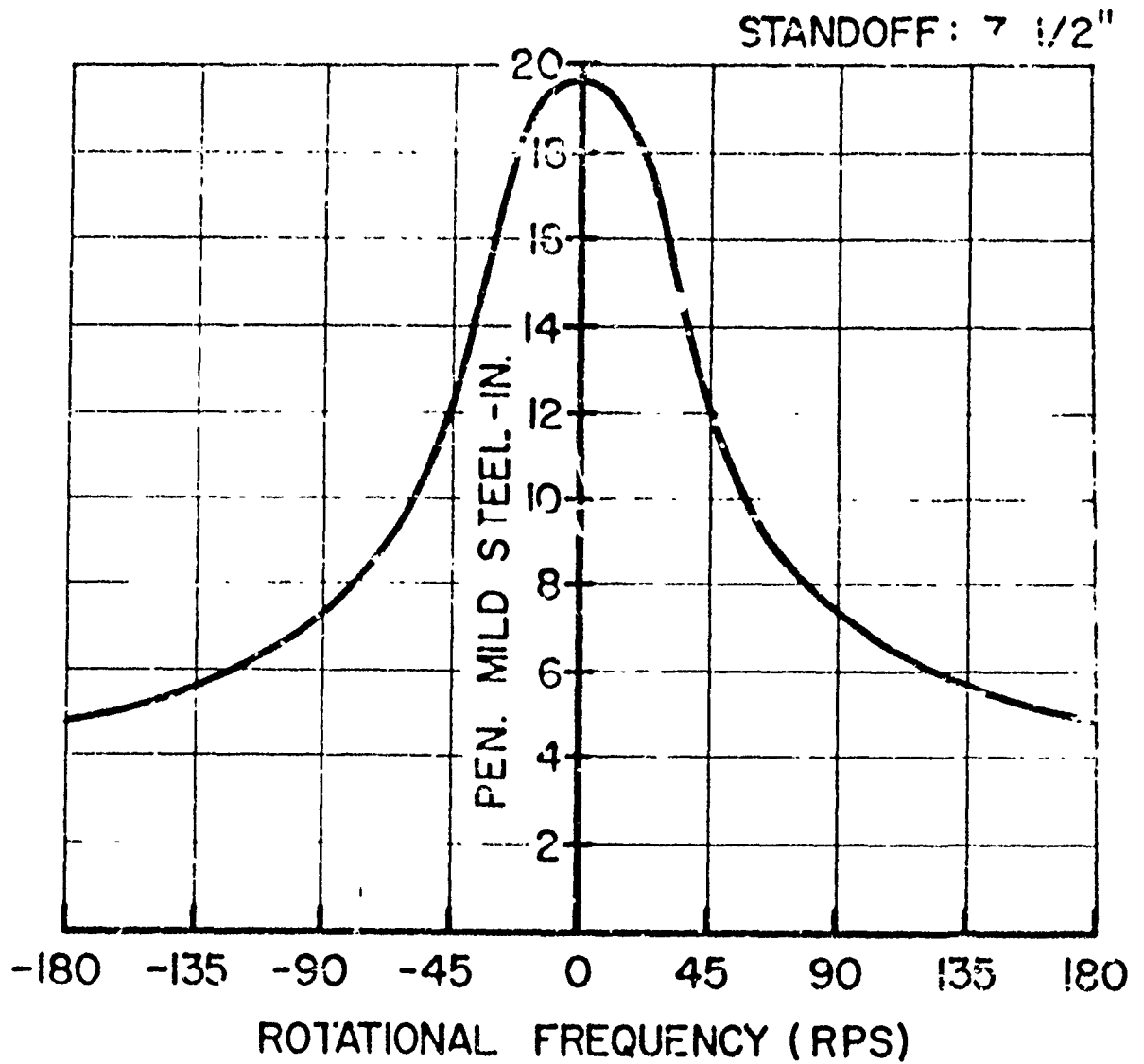
FIGURE 2

PENETRATION PERFORMANCE OF 105 MM
SMOOTH LINER UNDER ROTATION

SMOOTH FLUTED
VIEW OF INSIDE SURFACE

SMOOTH FLUTED
VIEW OF OUTSIDE SURFACE
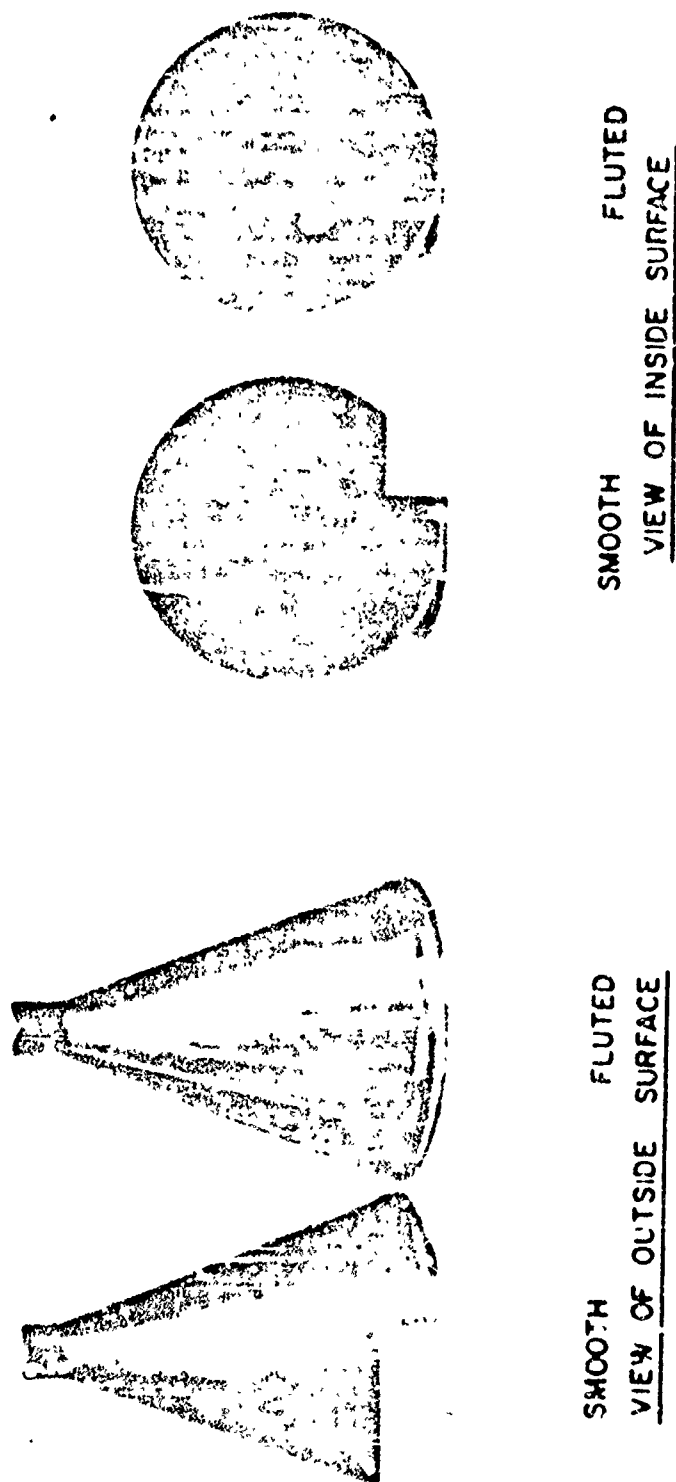
FIGURE 3

PHOTOGRAPHS OF EXTERIOR AND INTERIOR SURFACES OF SMOOTH AND
FLUTED LINERS. THE FLUTED LINERS WERE FORMED BETWEEN MATCHED TOOLS.

$\mu = \dfrac{a}{R}$, a = FLUTE DEPTH , R = PITCH RADIUS OF LINER ELEMENT

$\lambda = \dfrac{T}{R}$, T = WALL THICKNESS OF BLANK BEFORE FLUTING

n = NUMBER OF FLUTES

ψ = ANGLE BETWEEN FLUTE OFFSET AND RADIUS THROUGH ITS ROOT.

δ = ANGLE OF INDEXING (WHEN MATCHING FLUTED TOOLS ARE USED)
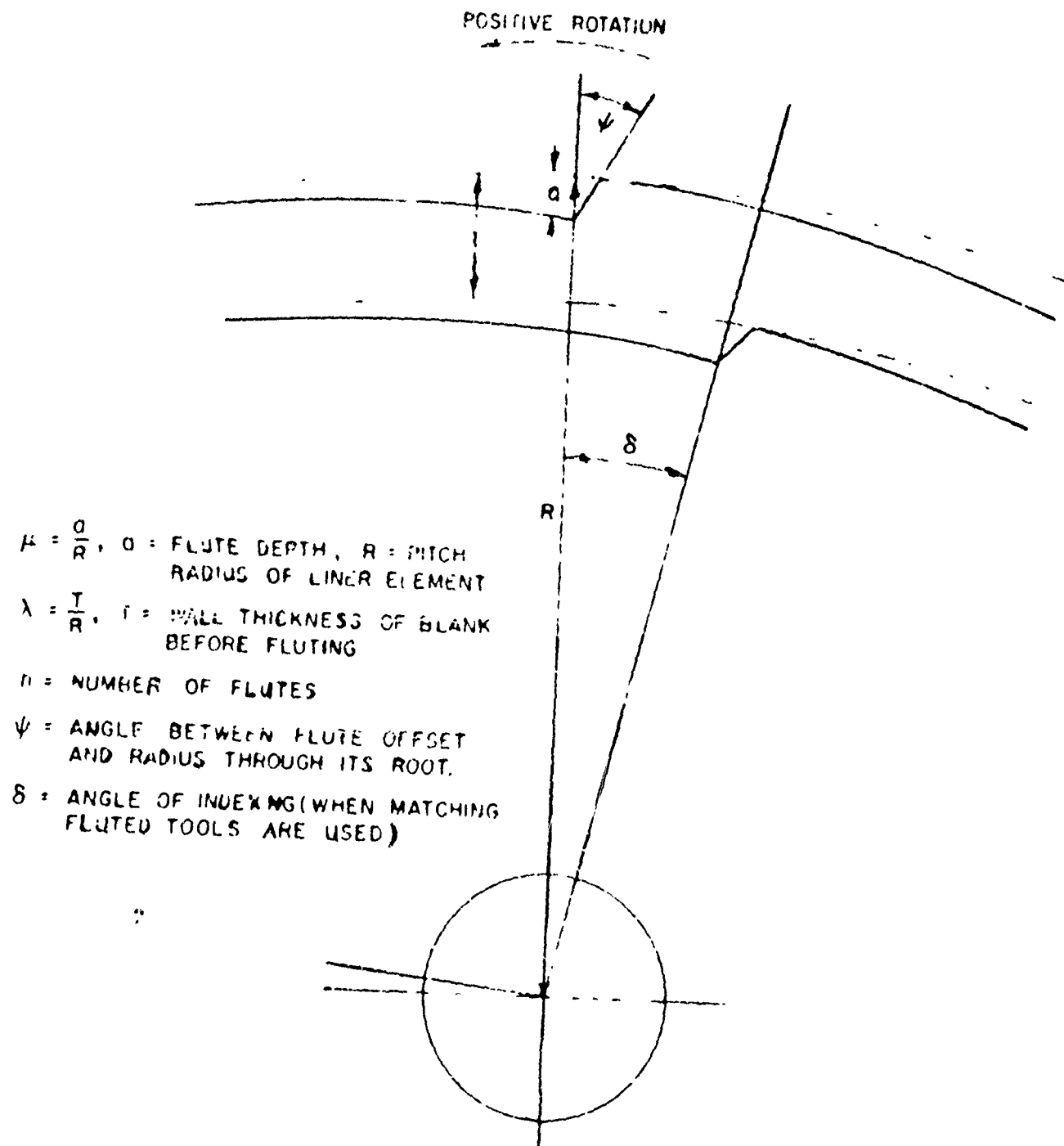
FIGURE 4

DEFINITION OF DESIGN PARAMETERS FOR FLUTED LINERS
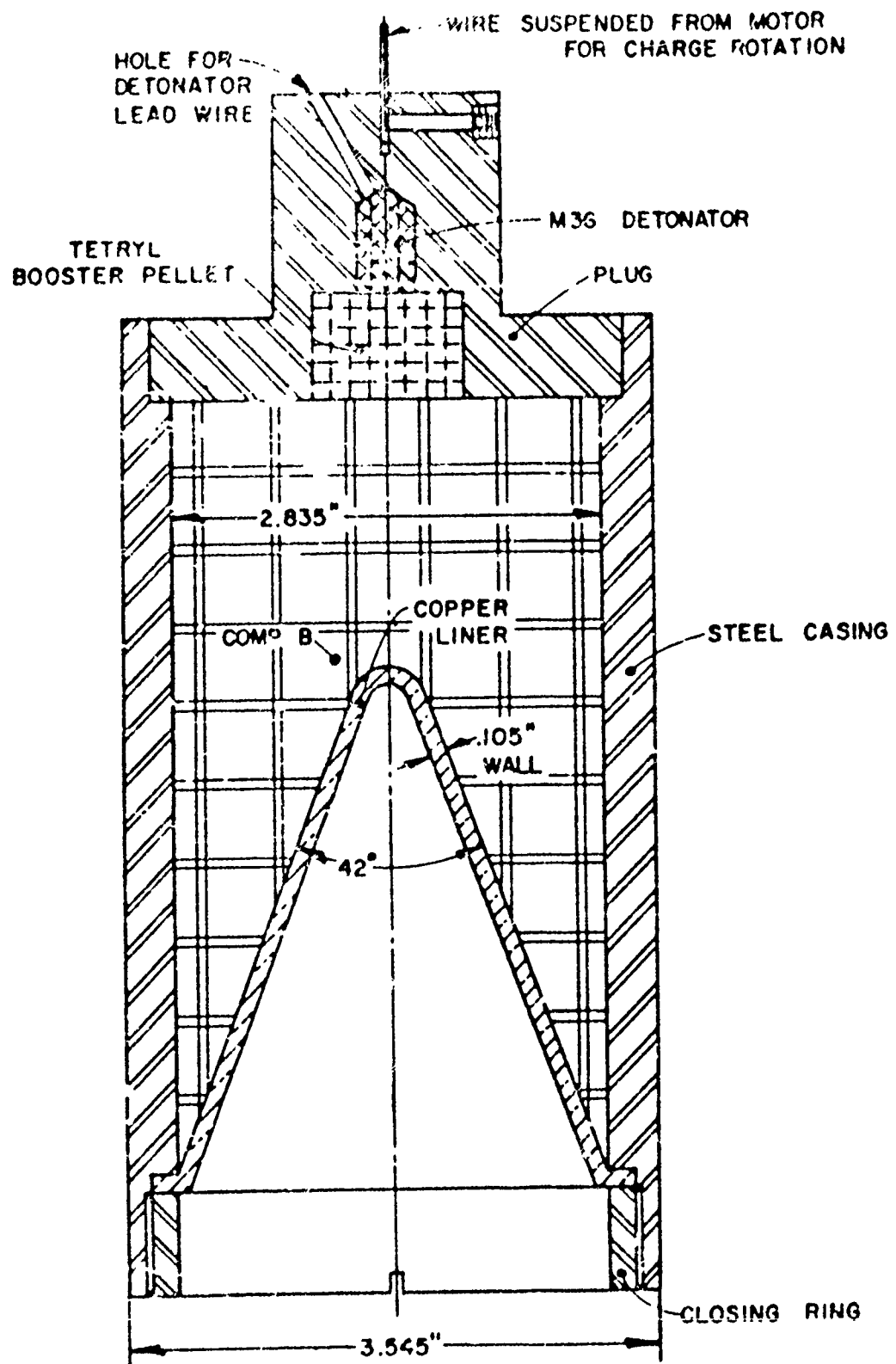
FIGURE 5   SCALED BRL.-3 CHARGE DESIGN
USED IN ROTATION EXPERIMENTS
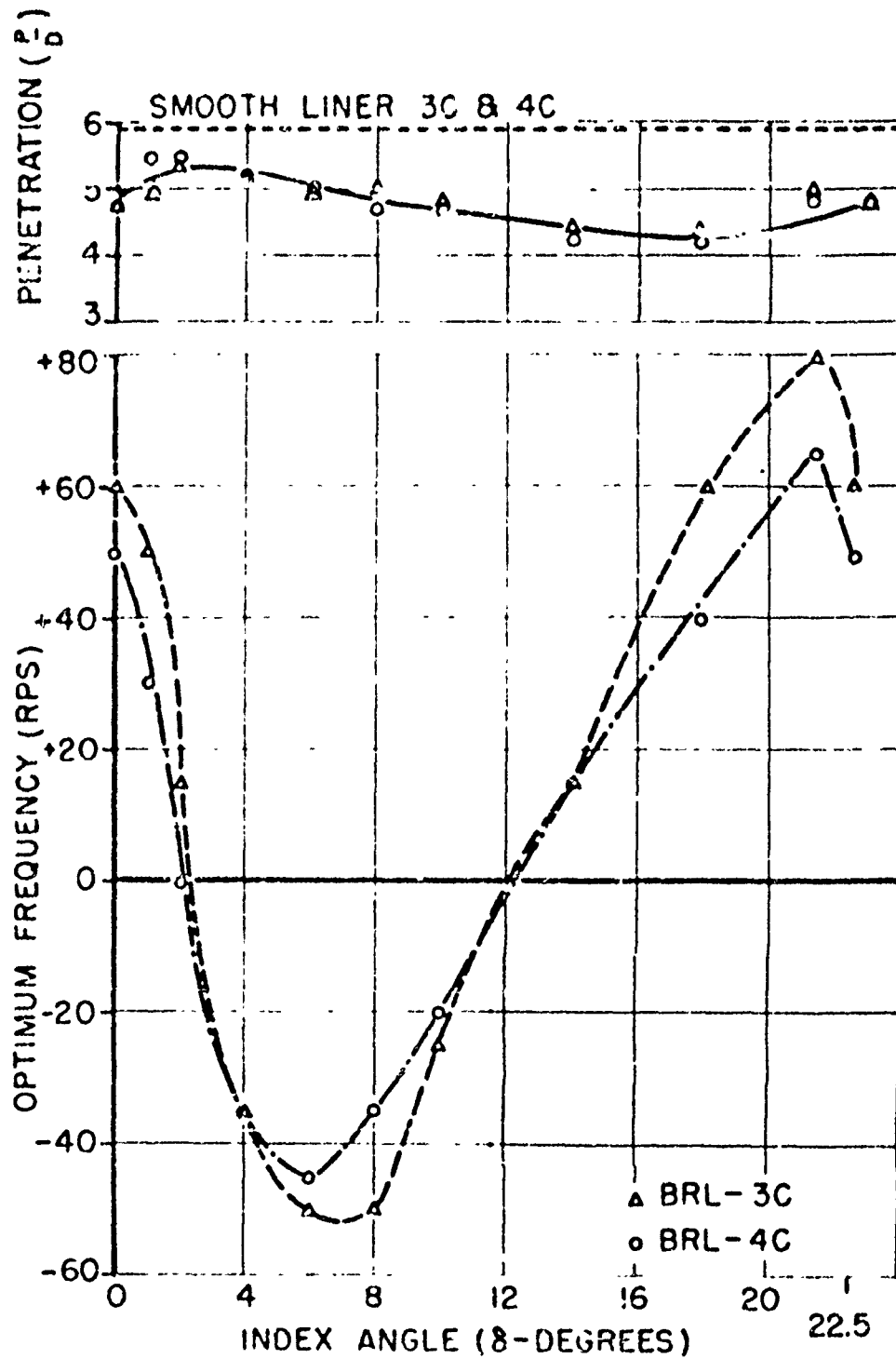
FIGURE 6

OPTIMUM FREQUENCY vs. INDEX ANGLE &
NORMALIZED PENETRATION vs. INDEX ANGLE
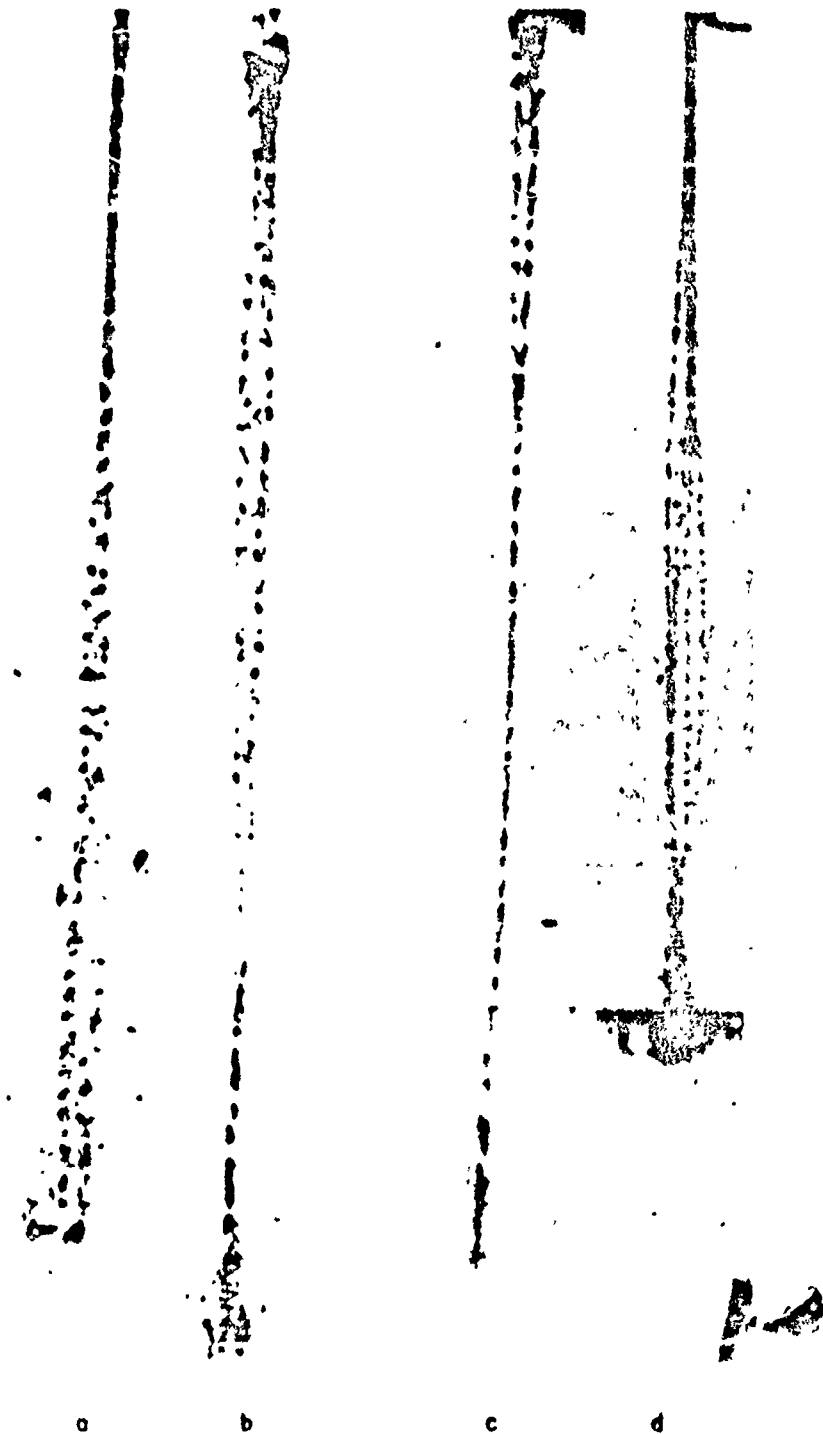
FIGURE 7
FLASH RADIOGRAPHS ILLUSTRATING VARIA-
TION IN OPTIMUM FREQUENCY ALONG CONE:

(a) $\delta = 0°$, $\nu = 120$ RPS   (c) $\delta = 6°$, $\nu = -100$ RPS

(b) $\delta = 0°$, $\nu = 30$ RPS   (d) $\delta = 6°$, $\nu = -20$ RPS
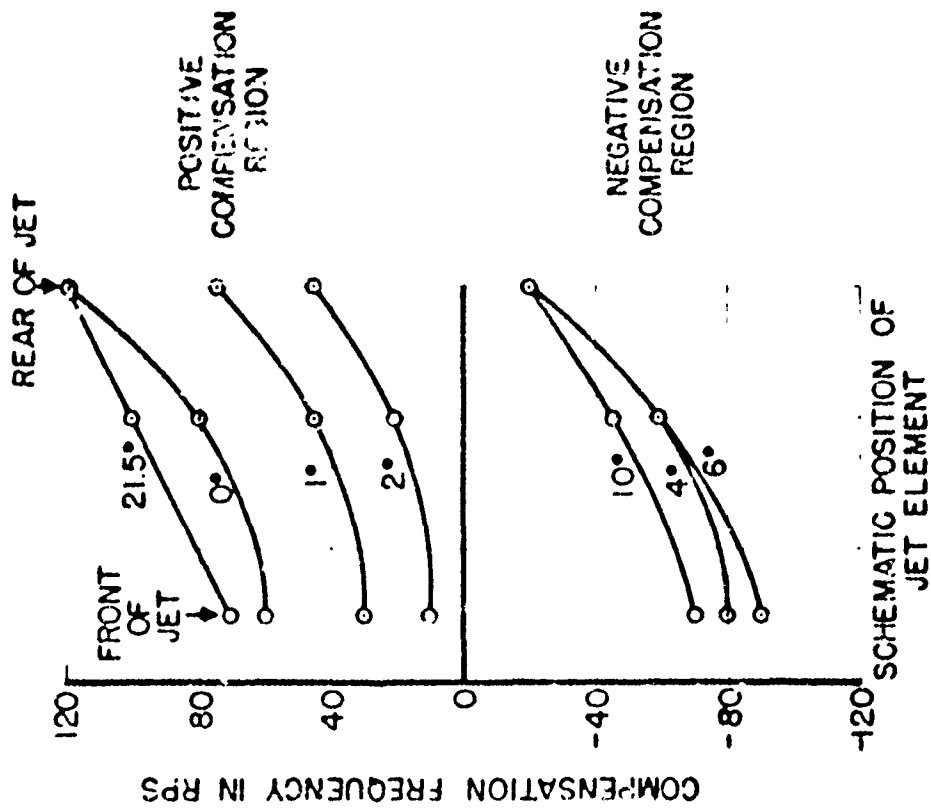
FIGURE 8

COMPENSATION FREQUENCIES OF ELEMENTS OF A JET, DEDUCED FROM FLASH RADIOGRAPHS. INDEX ANGLES ARE SHOWN ON EACH CURVE FOR A SCALE 3C LINER

CONFIDENTIAL
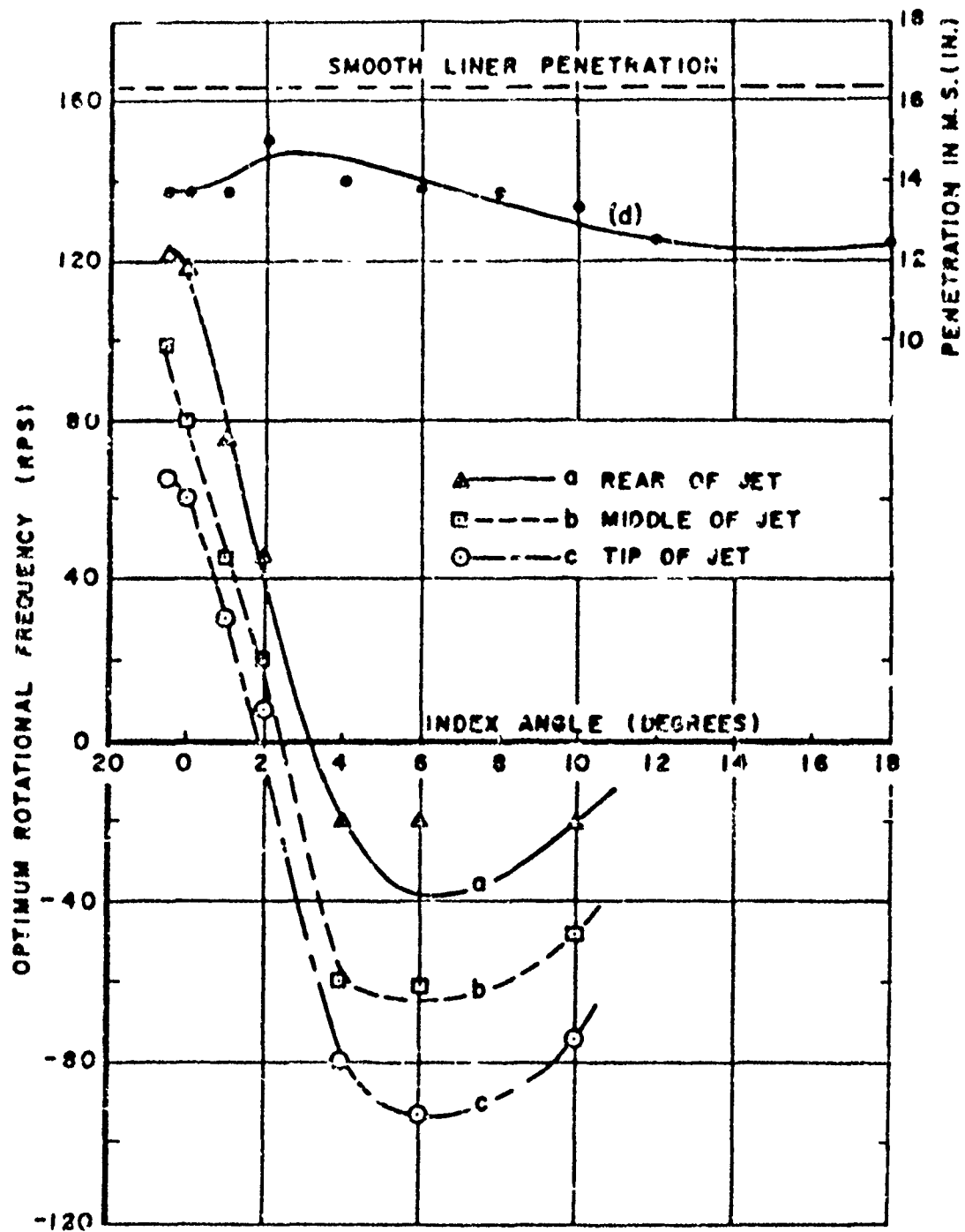
FIGURE 9

ROTATION vs. INDEX ANGLE
IDEAL CURVES FOR LINEAR FLUTED LINERS
DATA DEDUCED FROM FLASH RADIOGRAPHS
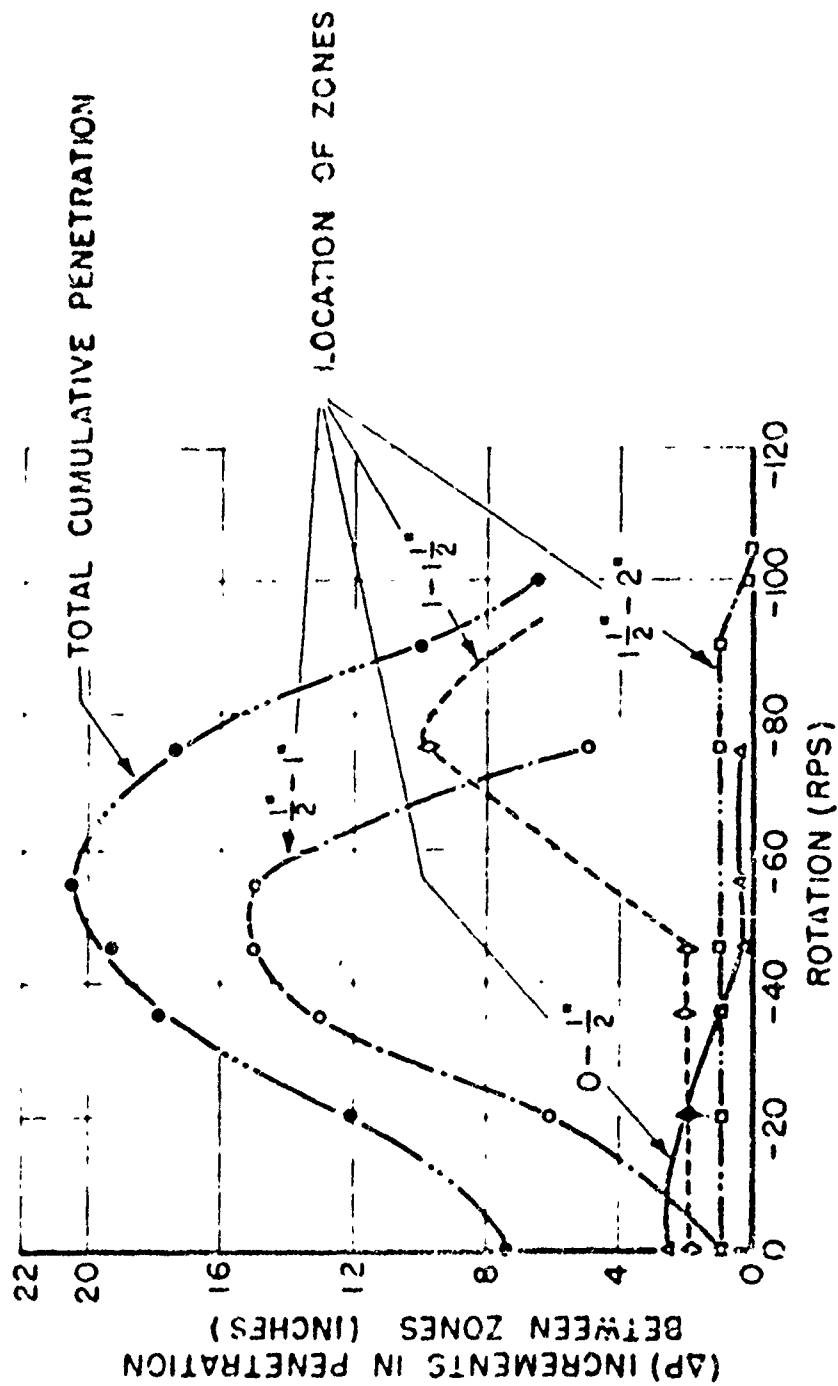
CONFIDENTIAL

FIGURE 10

PENETRATION VS ROTATION FOR VARIOUS ZONES OF A FLUTED LINER

BRL-4, 3.78" {0.140" (16 x .0400") (S,S)(6")}

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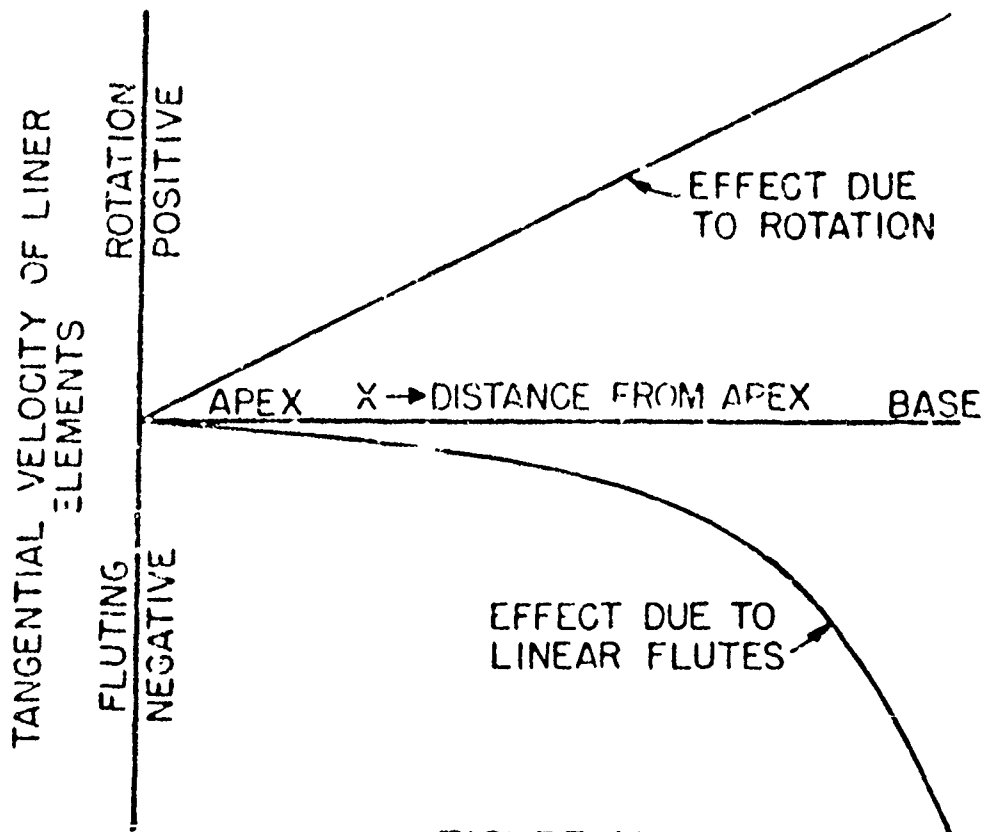
FIGURE II
TANGENTIAL VELOCITIES OF ELEMENTS OF A LINEAR FLUTED
LINER
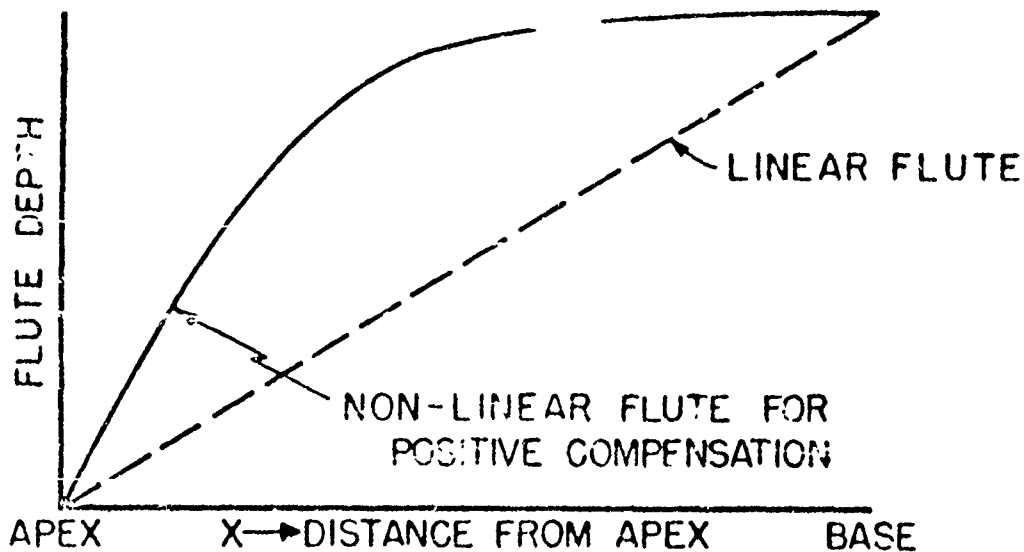
FIGURE 12
NON - LINEAR FLUTE DEPTH DESIGN TO PROVIDE COMPEN-
SATION IN POSITIVE ROTATION DIRECTION

32
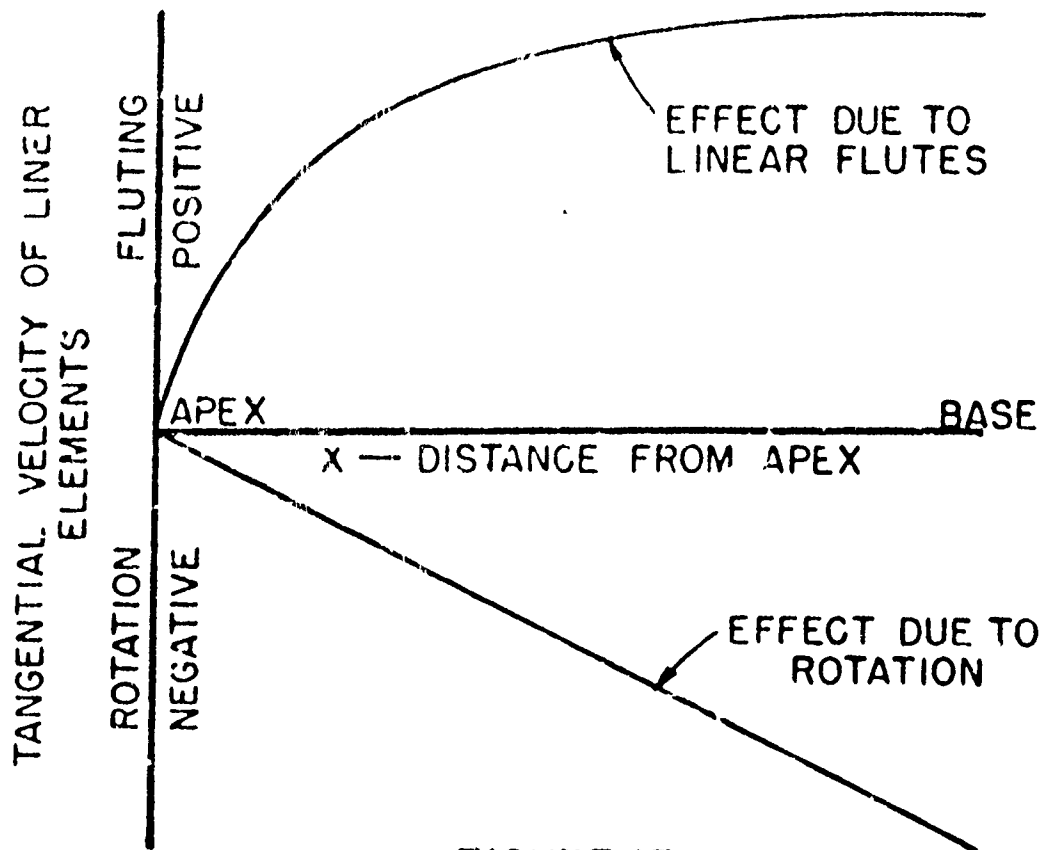
FIGURE 13
TANGENTIAL VELOCITIES OF ELEMENTS OF A
LINEAR FLUTED LINER
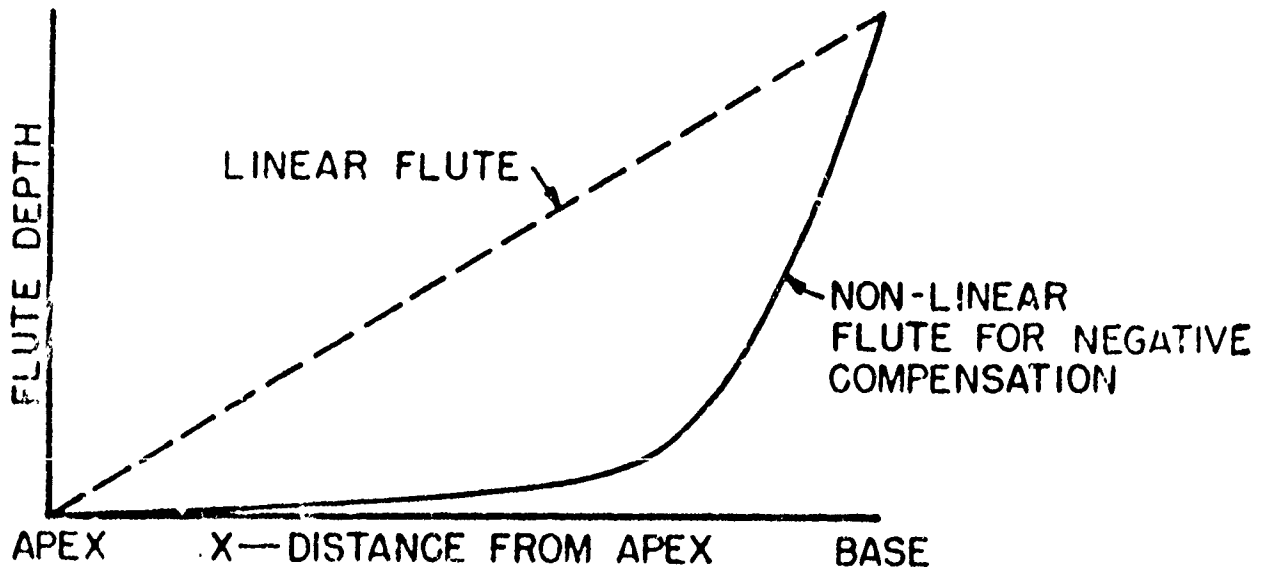
FIGURE 14
NON-LINEAR FLUTE DEPTH DESIGN TO PROVIDE
COMPENSATION IN NEGATIVE ROTATION DIRECTION

33
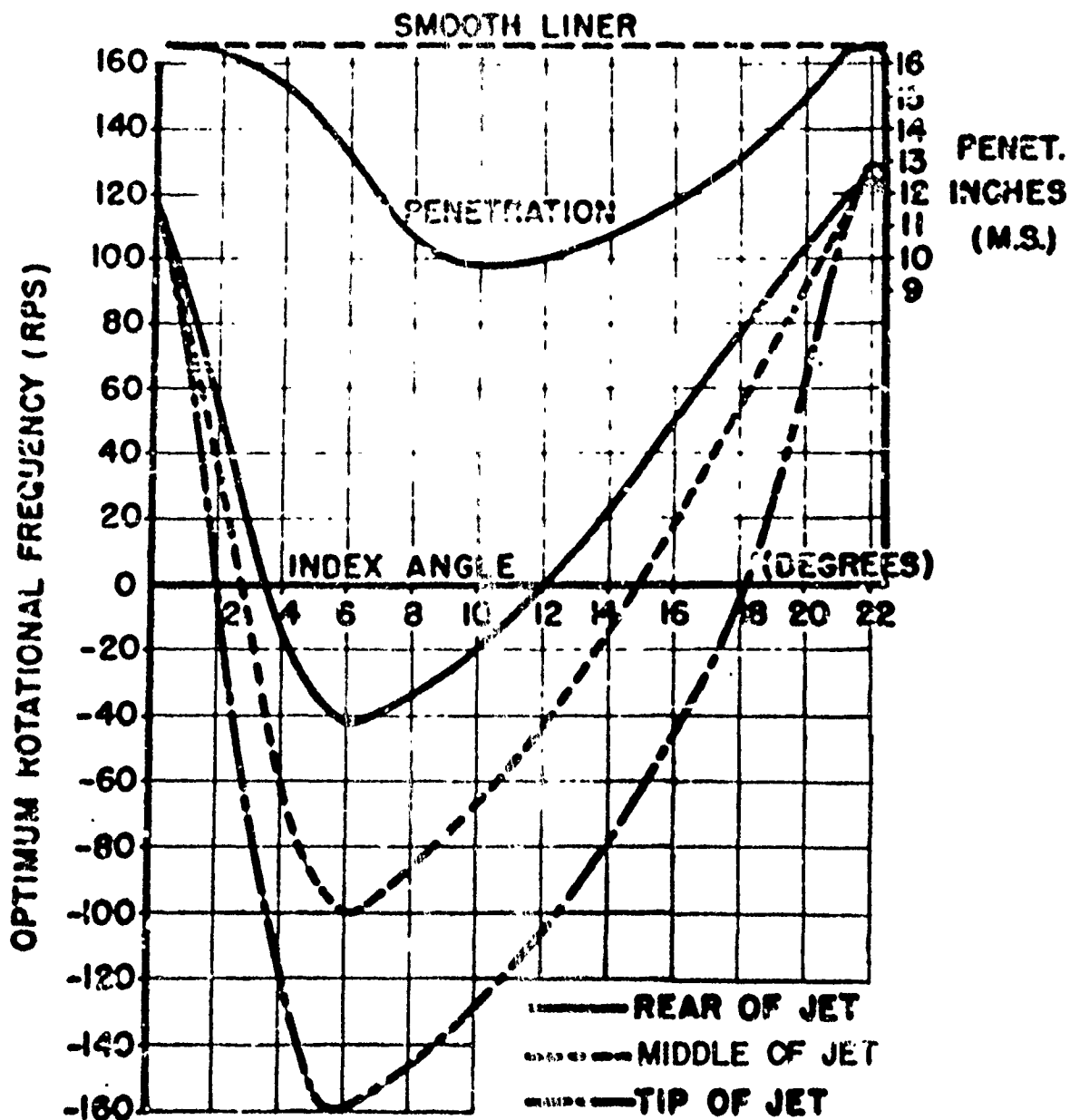
FIGURE 15
HYPOTHETICAL CURVES FOR LINER COMPENSATED
AT 120 RPS WITH 0° INDEX ANGLE
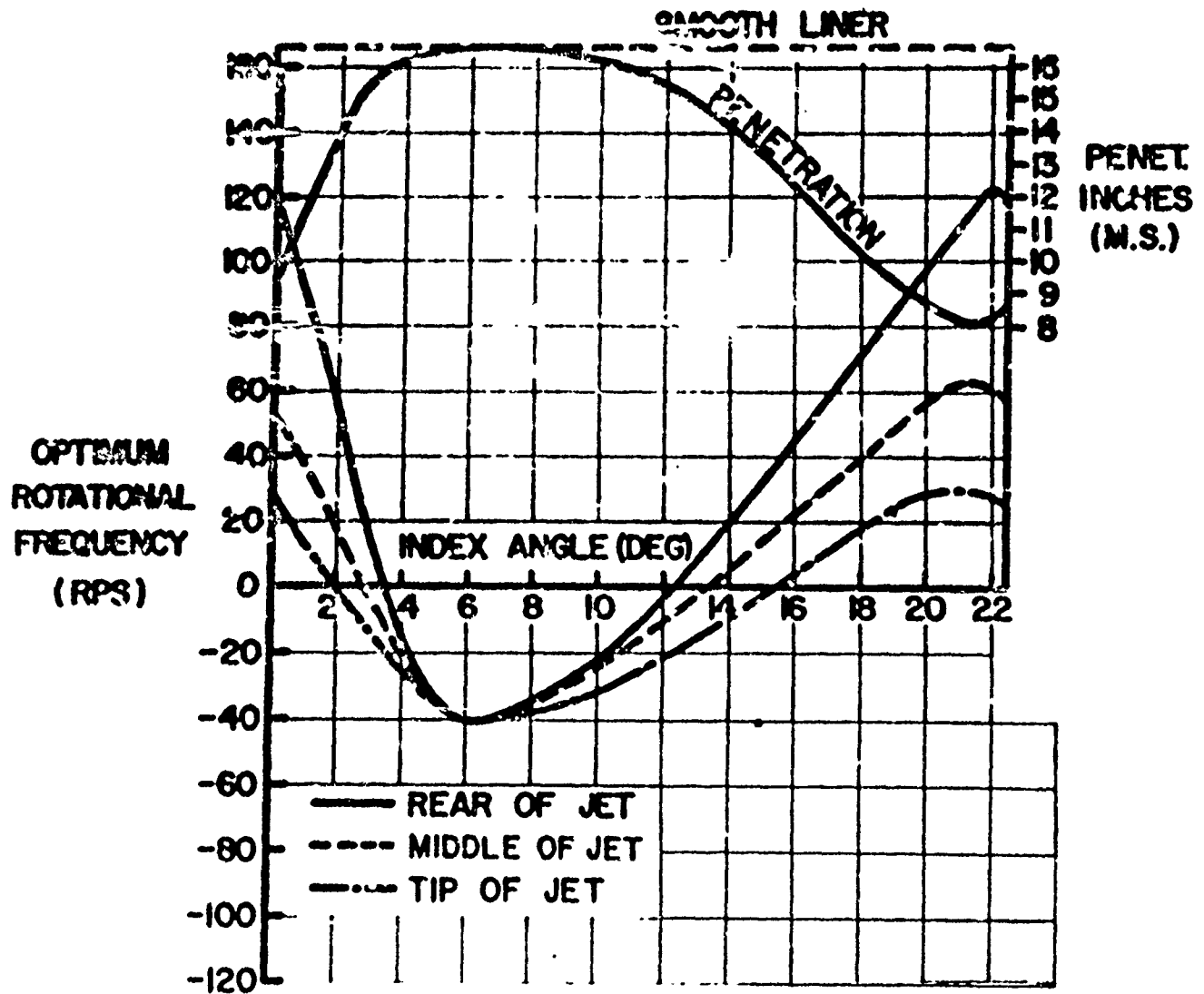
FIGURE 16
HYPOTHETICAL CURVES FOR LINER COMPENSATED AT
-40 RPS WITH 6° INDEX ANGLE

35
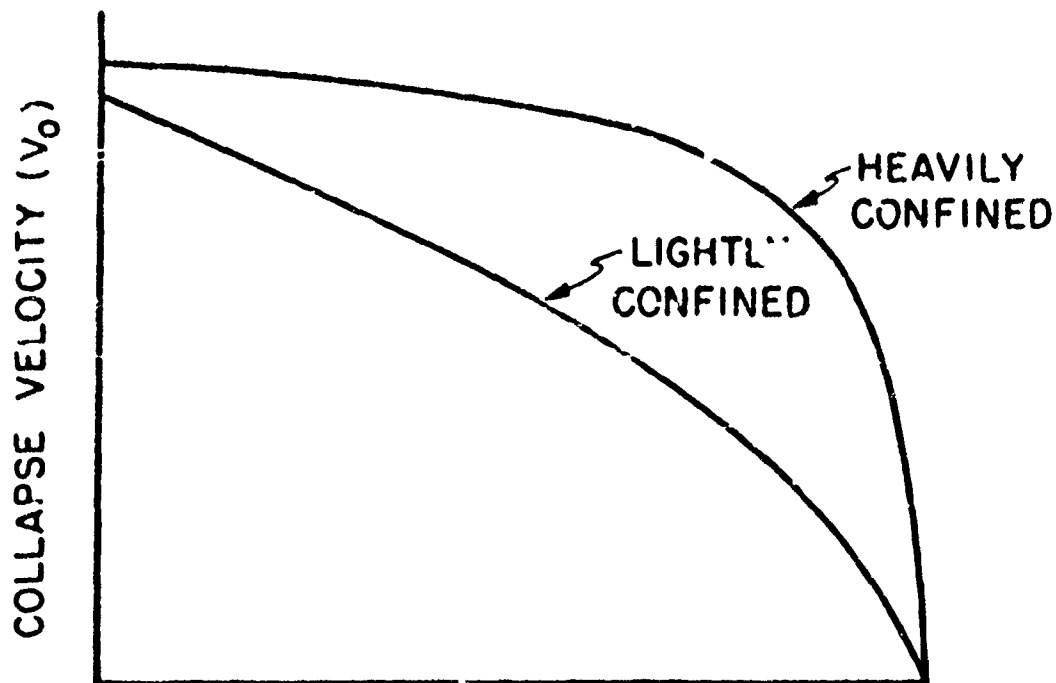
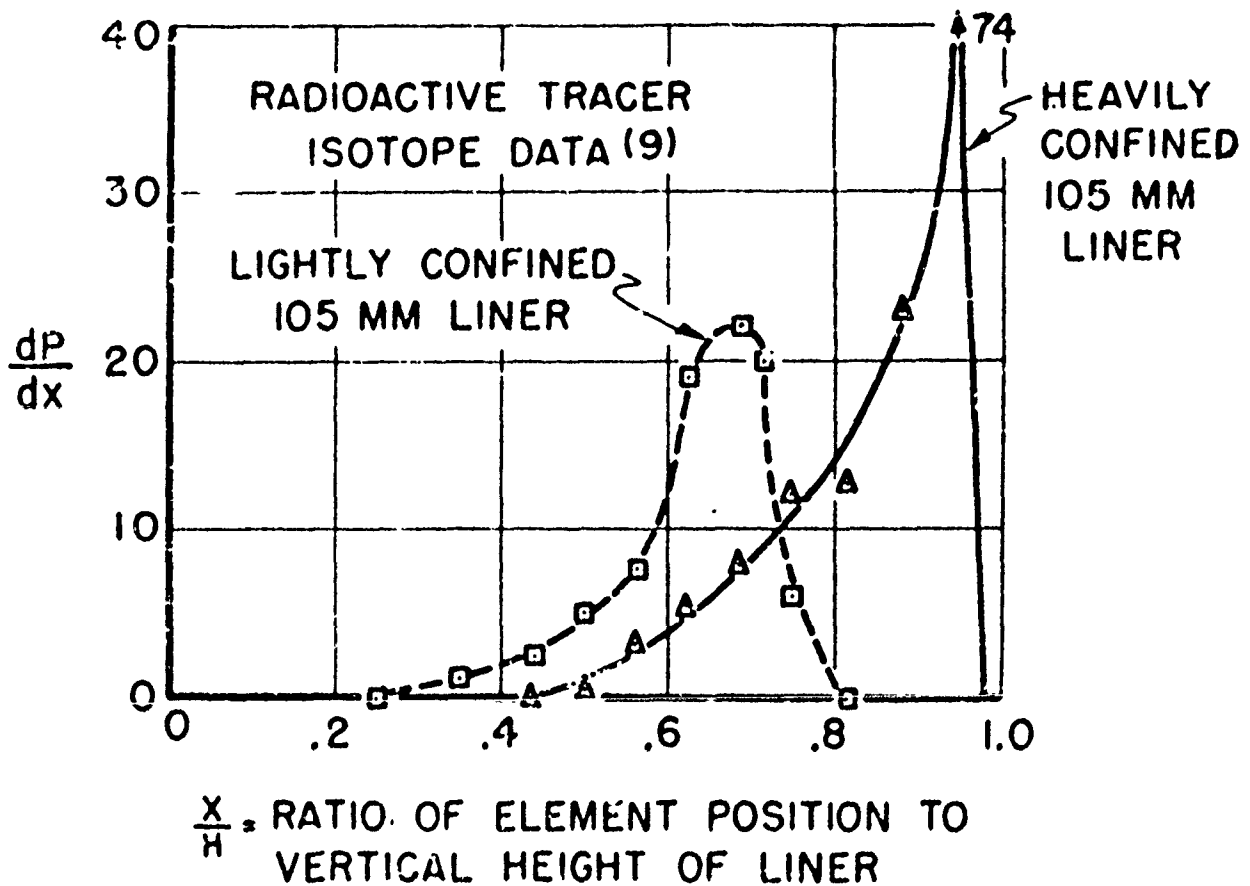FIGURE 17 – EFFECT OF CONFINEMENT ON COLLAPSE VELOCITY REPRESENTED SCHEMATICALLY
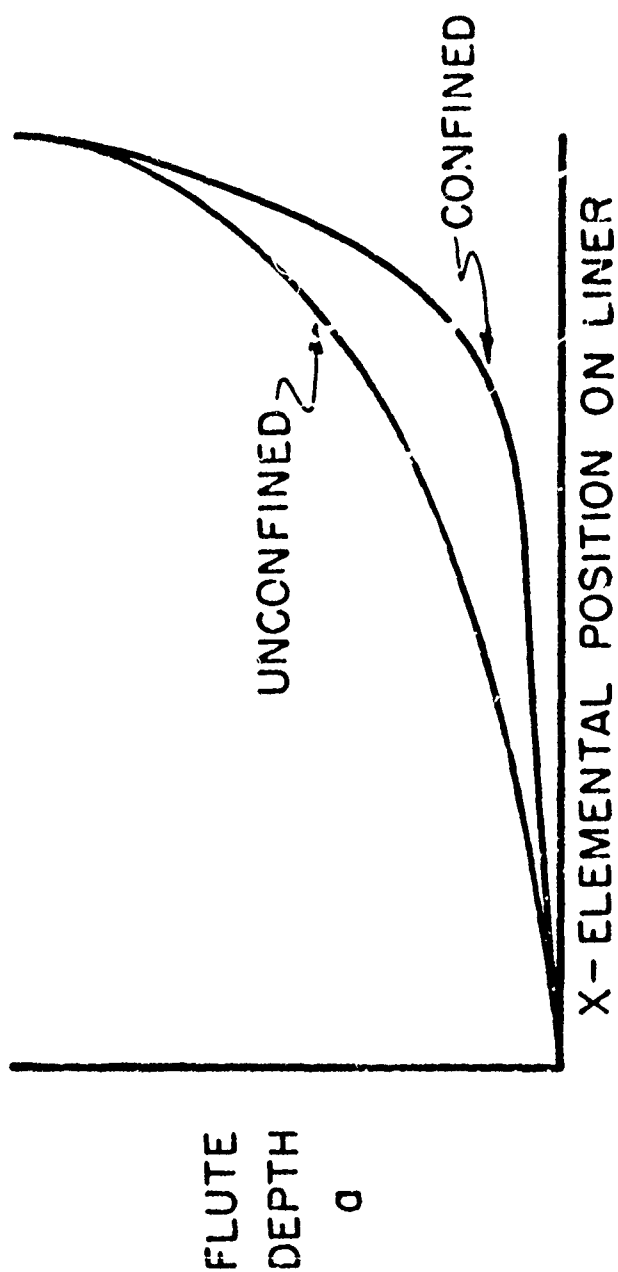

FIGURE 18 – $\dfrac{dP}{dx}$ VS. ELEMENTAL POSITION OF LINER

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FIGURE 19

SCHEMATIC OF FLUTE DEPTH VS. POSITION ON LINER FOR
LIGHTLY AND HEAVILY CONFINED CHARGES, FOR A
NEGATIVE COMPENSATION REGION

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r = RADIUS OF LINER ELEMENT
a = FLUTE DEPTH OF LINER ELEMENT
a_b = FLUTE DEPTH AT BASE OF LINER
R_b = RADIUS OF ELEMENT AT BASE
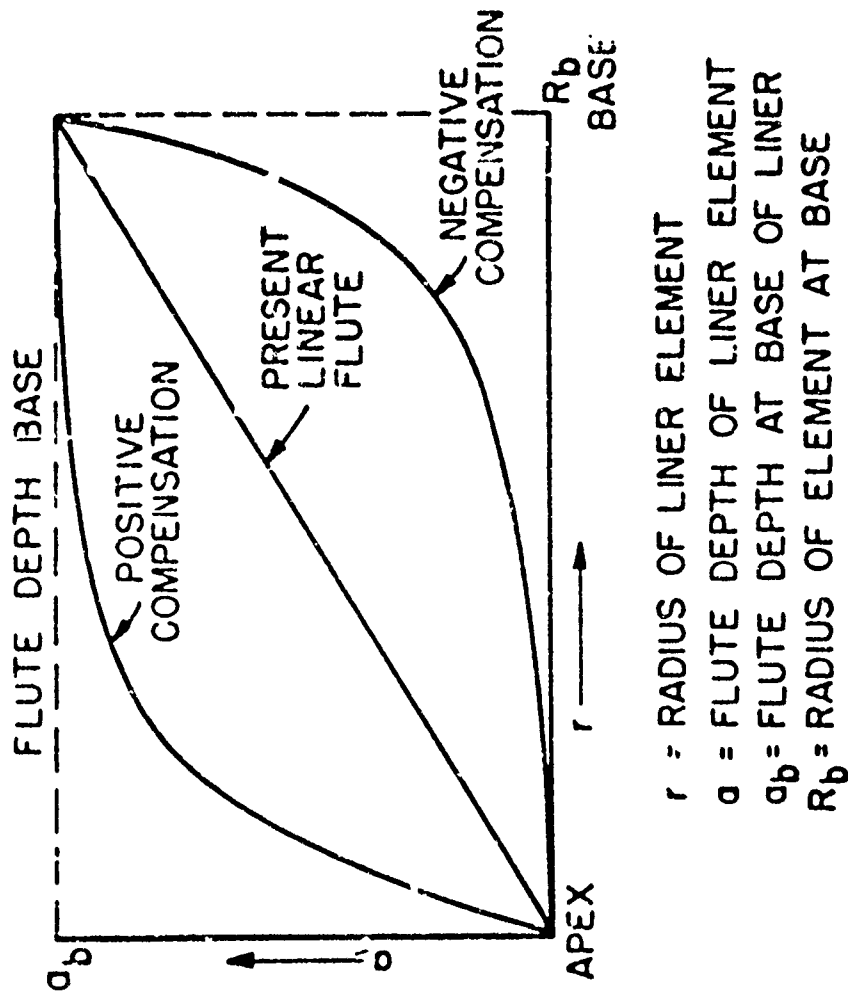
FIGURE 20
NON-LINEAR FLUTE DESIGN
DEDUCED FROM FLASH RADIOGRAPHS
HEAVILY CONFINED CHARGES